A 3D finite element model to investigate elastic heterogeneity and topography effects on 2010 M_w 7.2 El Mayor Cucapah coseismic deformation using space geodetic data

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Outline

- Motivations
- Targeting a complex event: The El Mayor Cucapah Earthquake
- From analytical to numerical inverse solution: the FEM model
- Results
- Conclusions and next steps

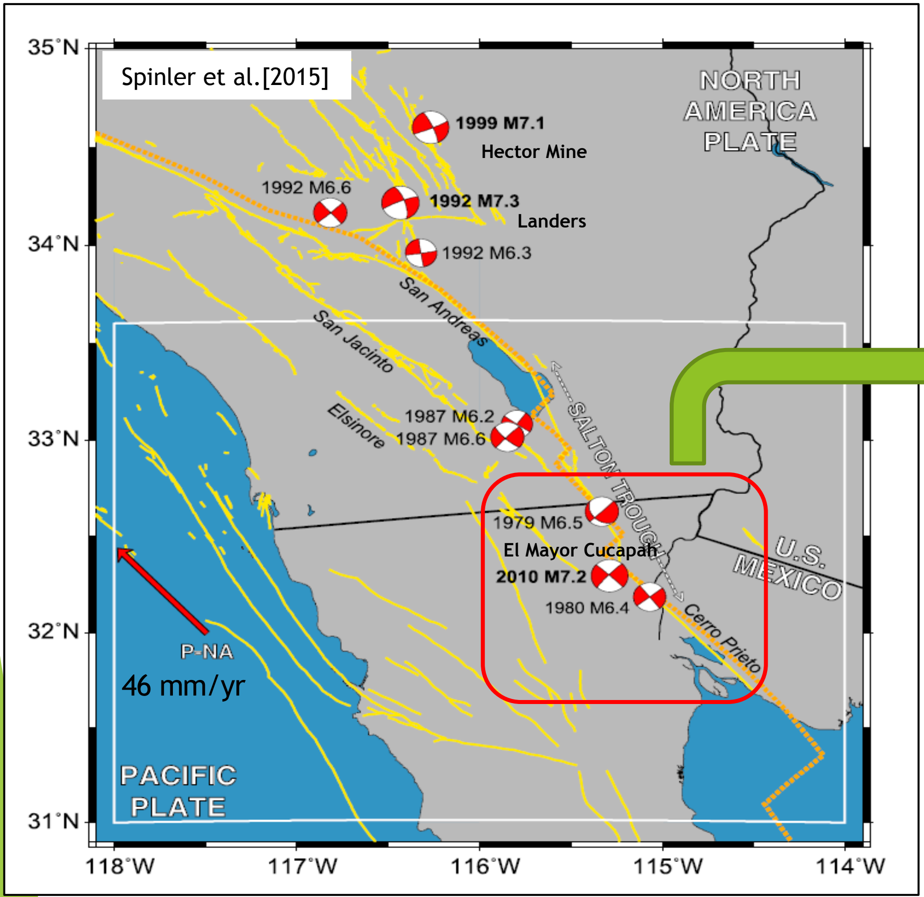
Motivations

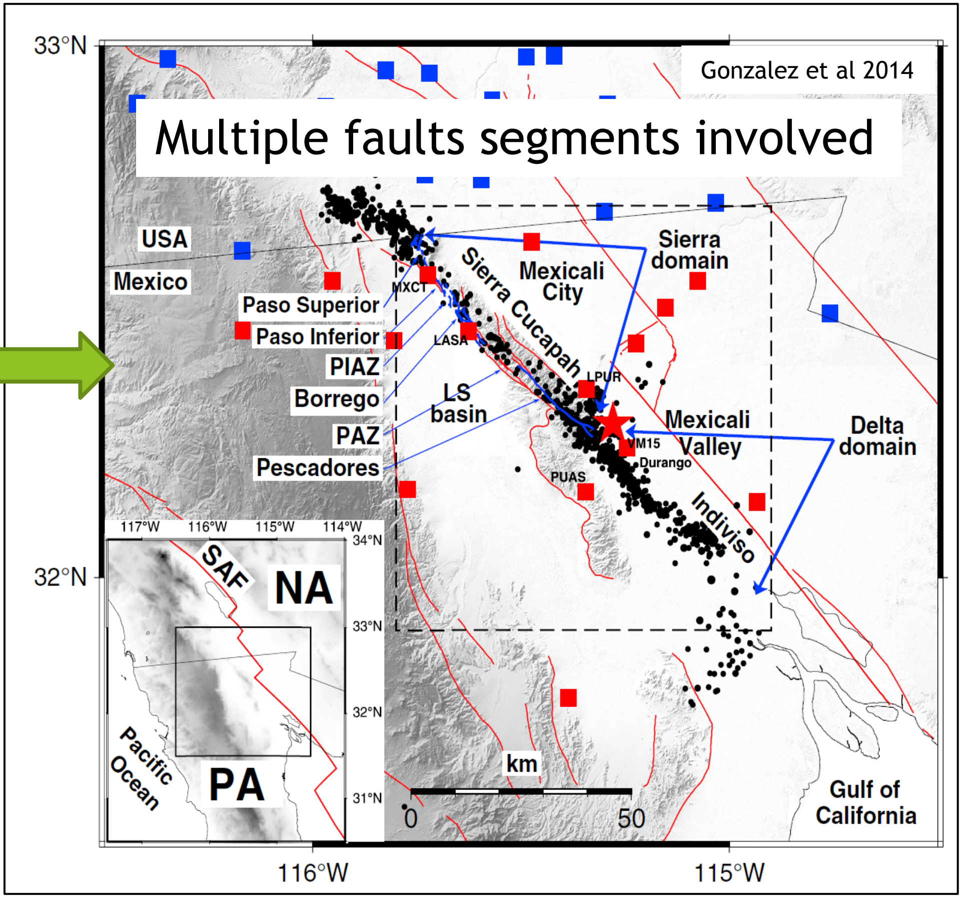
Analytical finite fault inversions are based on some simplified assumptions:

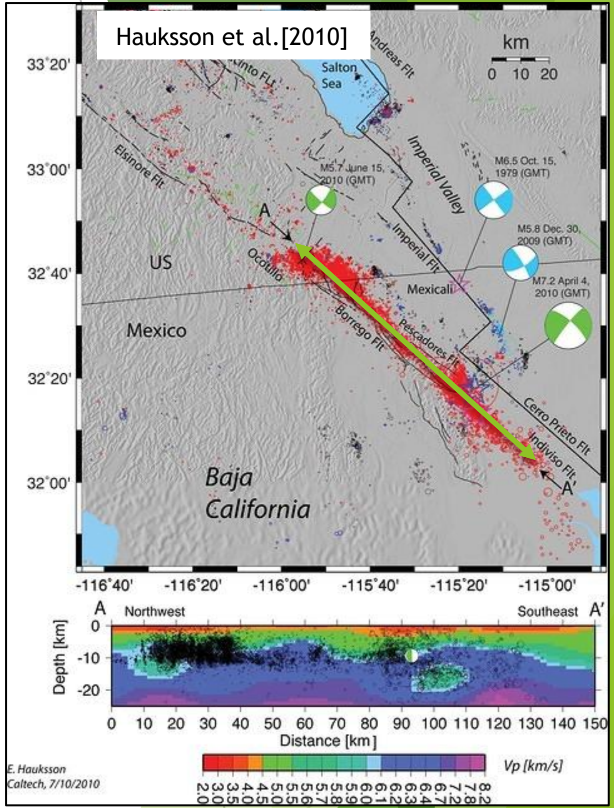
- The domain is treated as an infinite linear elastic halfspace (no topography);
- Material properties are limited to homogeneous or layered configurations (no full heterogeneities);
- Subsurface sources are treated as independent (no fault to fault interaction).

Are these assumptions sufficient to accurately explain complex tectonic events?

The El Mayor Cucapah earthquake







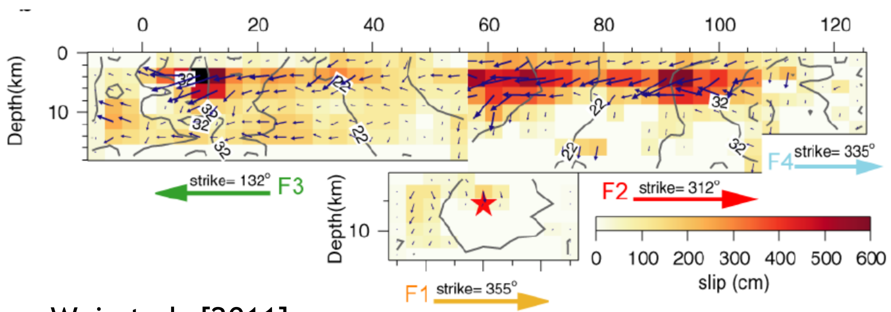
Strong change in Vp structure

Location: Northeastern Baja California
Event occurrence: 4th April 2010
Magnitude M_w7.2
Depth 10 km

Bidirectional rupture (~120km) in NW-SE direction
Right-lateral strike-slip with some normal faulting

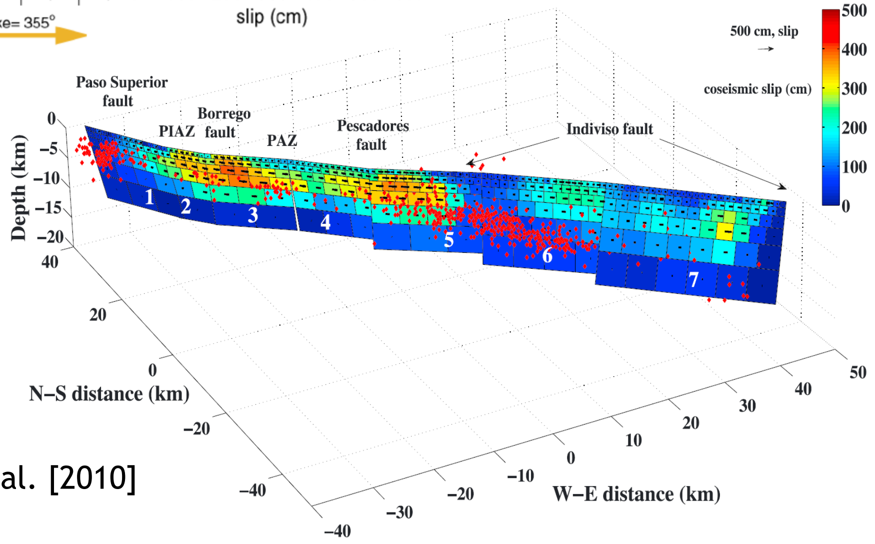
Complex Event

The El Mayor Cucapah Event: previous studies



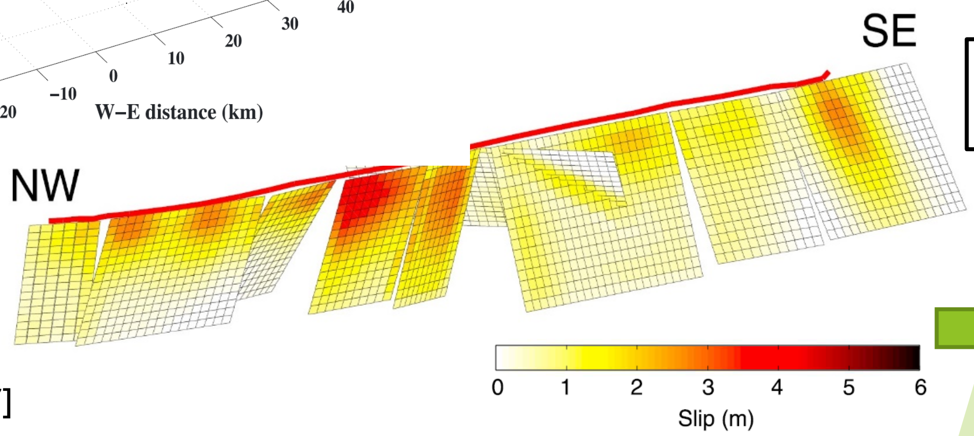
Wei et al. [2011]

Joint inversion of seismic and geodetic data
4 segment fault geometry



Fialko et al. [2010]

Joint inversion geodetic data
7 segment fault geometry

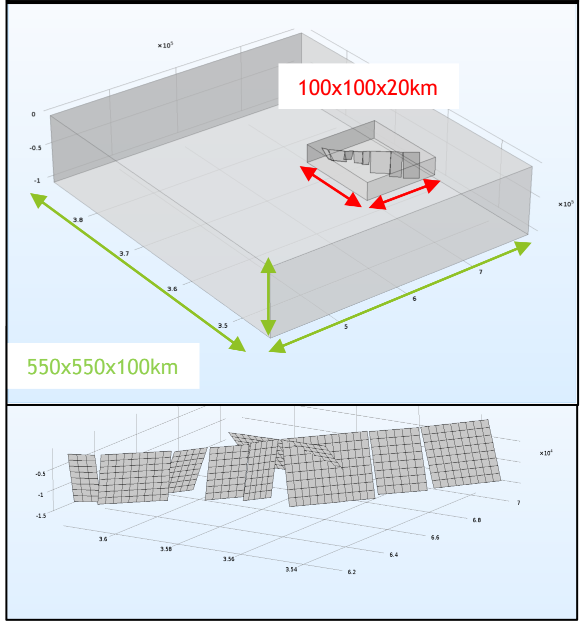


Huang et al.[2017]

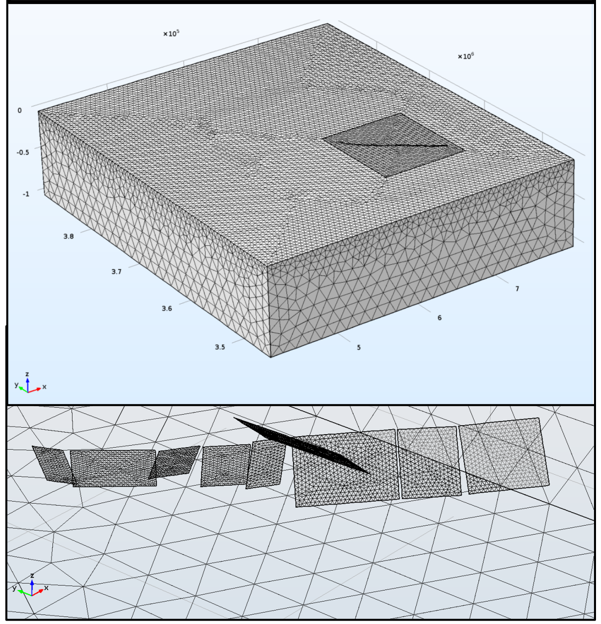
Joint inversion of geodetic data
9 segment fault geometry

Chosen solution

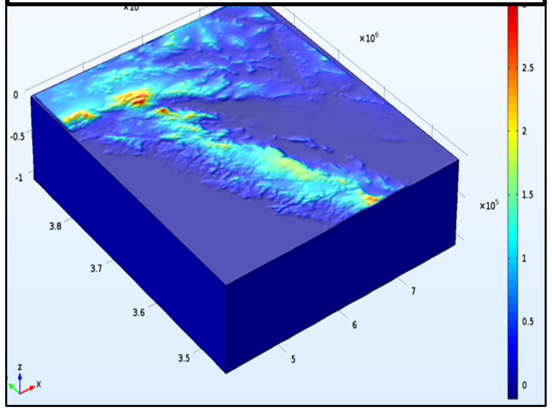
Geometry



Mesh (global)



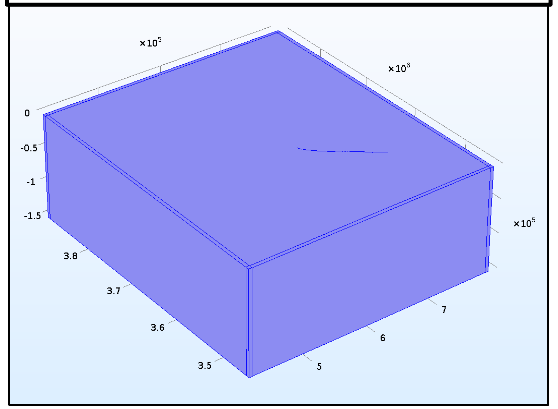
Topography



Digital elevation model is included from Shuttle Radar Topography Mission (30m resolution).

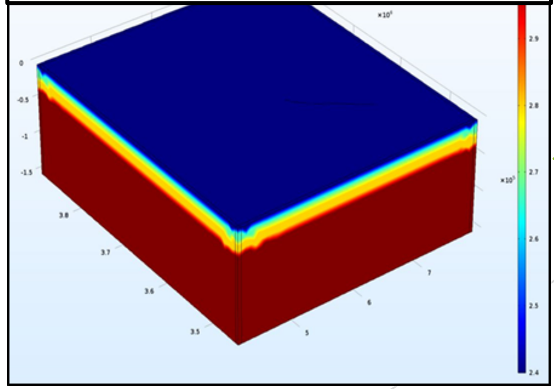
ftp://e0srp01u.ecs.nasa.gov/srtm/version2/SRTM3/

Homogeneous Model



Homogeneous Model Parameters			
Depth(Km)	Density(Kg/m^3)	E(GPa)	v
0-100	2400	60.75	0.25

Layered Model



Layered Model Parameters			
Depth(Km)	Density(Kg/m^3)	E(GPa)	v
0-5.5	2400	60.75	0.25
5.5-16.0	2670	88.5	0.25
16.0-32.0	2800	104.75	0.25
32.0-100	3000	151.75	0.25

Boundary Conditions

- Lateral Sides: Roller+ infinite elements
- Bottom: Fixed
- Top surface: Free
- Faults: Thin Elastic Layers

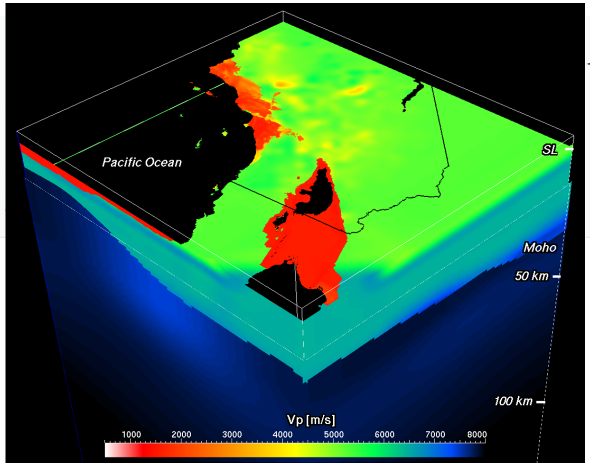
Chosen area is big enough to further extract GPS SAR and Optical data results

Infinite elements assure no boundary effects

Mesh is refined on internal domain and fault planes

Inclusion of material heterogeneities

Model incorporates the data from SCEC Community Velocity Model Harward (v 15.1.1)

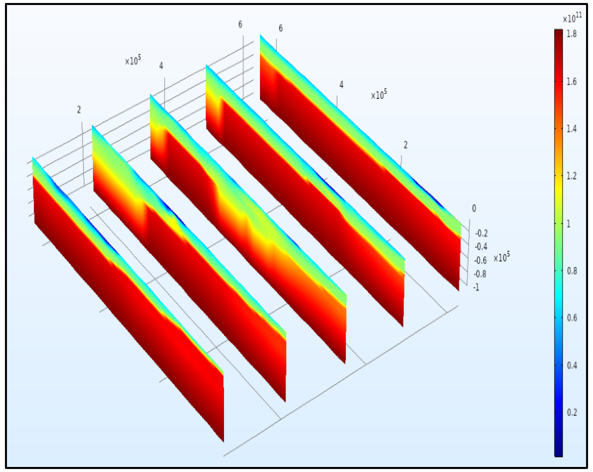


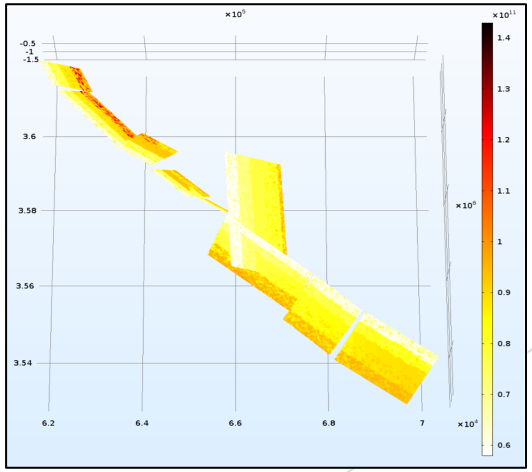
vp	vs	rho
-99999.00	-99999.00	-99999.00
5575.15	3132.10	2631.81
4554.52	2313.56	2469.78
5066.61	2916.30	2545.10
5372.79	3024.30	2595.55
4181.37	2432.22	2418.45
6533.31	3776.40	2841.47
4997.06	2889.03	2534.30

$$\mu = \rho \cdot Vs^2$$
$$\lambda = (Vp)^2 \cdot \rho - 2\mu$$

$$E = \frac{9K\lambda}{3K + \mu}$$
$$\sigma = \frac{\lambda}{2 \cdot (\lambda + \mu)}$$

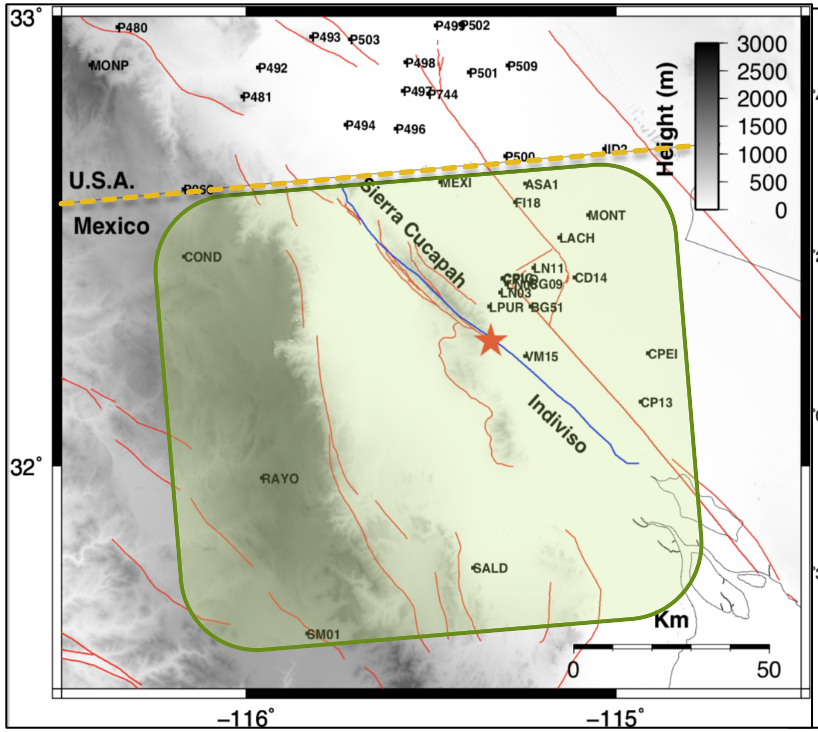
Heterogeneous Model Parameters			
Depth(Km)	Density(Kg/m^3)	E(GPa)	v
0-100	1930-3400	2.5e9 - 1.8e11	0.16-0.45

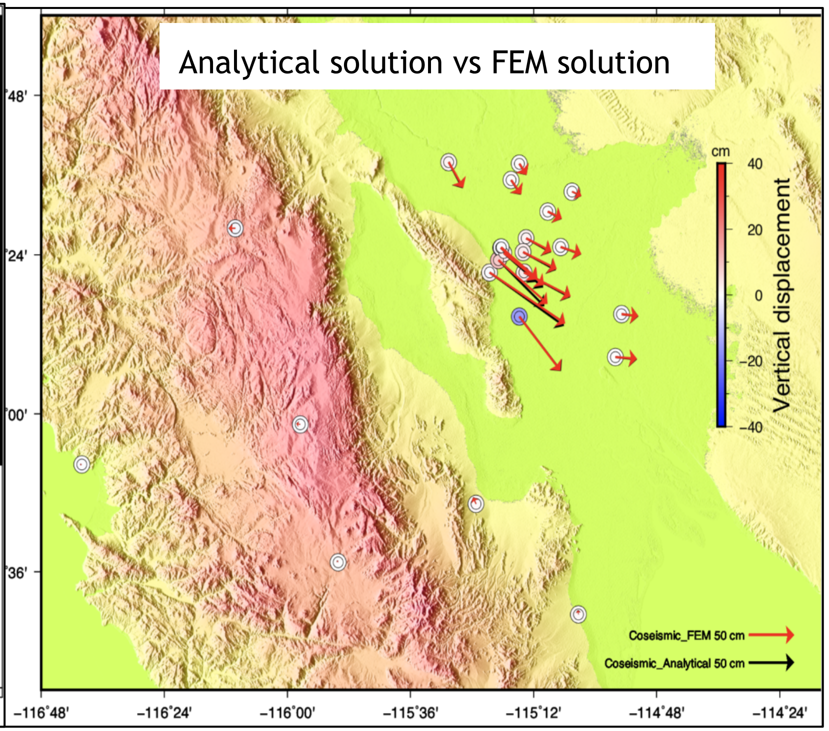


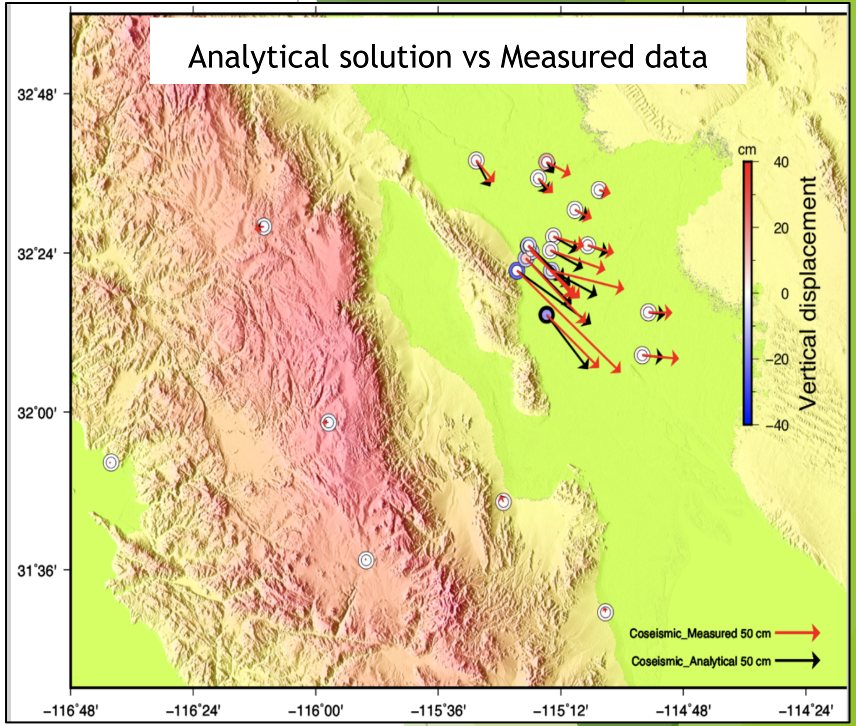


Young's modulus plotted on fault planes. Values increase at depth.

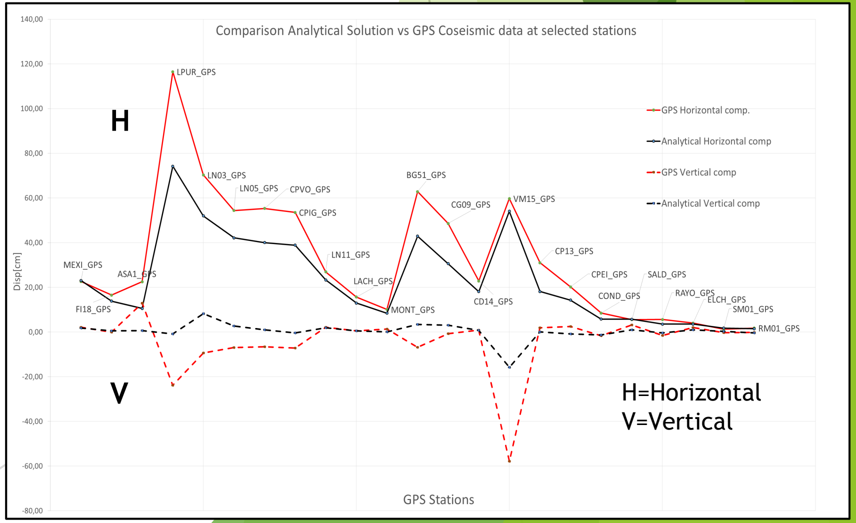
FEM Validation on near-field GPS stations (CICESE campaign)







Does this solution fit the GPS measurements?



Can the analytical solution be optimized? →YES

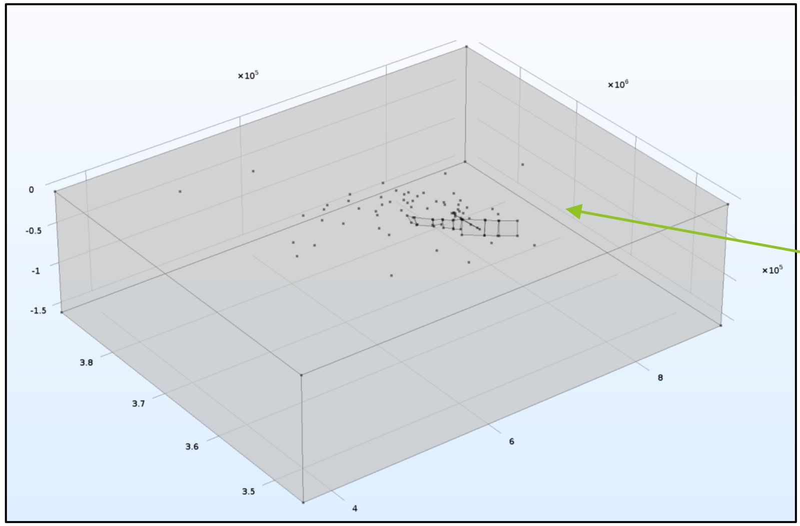
Optimization procedure

Coseismic Surface data (GPS)

Inversion

```
* EMC EARTHQUAKE COSEISMIC DISPLACEMENTS ESTIMATES
*  Long.     Lat.        E        N       U     dE      dN     dU    SITE
*  (deg)    (deg)               (cm)                   (cm)
```

Long. (deg)	Lat. (deg)	E	N (cm)	U	dE	dN (cm)	dU	SITE
244.657	32.356	86.90	-77.60	-23.80	0.40	0.40	1.80	LPUR_GPS
244.776	32.442	25.90	-7.30	2.10	0.90	0.60	2.80	LN11_GPS
244.846	32.509	14.20	-6.60	0.50	0.60	0.60	2.40	LACH_GPS
244.925	32.559	9.70	-2.70	1.30	0.60	0.60	2.40	MONT_GPS
244.686	32.387	50.20	-49.20	-9.40	0.40	0.40	2.00	LN03_GPS
244.754	32.629	20.30	-9.70	12.90	0.80	0.40	2.40	ASA1_GPS
244.703	32.405	40.90	-35.80	-6.90	0.40	0.40	1.80	LN05_GPS
244.888	32.420	22.10	-5.80	0.90	0.60	0.60	2.60	CD14_GPS
244.769	32.356	61.20	-14.10	-6.80	0.40	0.40	2.00	BG51_GPS
244.766	32.407	46.20	-15.00	-0.80	0.40	0.40	2.00	CG09_GPS
244.754	32.245	43.90	-40.50	-57.90	1.00	0.60	2.80	VM15_GPS
245.066	32.143	30.90	-2.70	1.90	0.40	0.50	2.20	CP13_GPS
245.086	32.251	20.20	-0.30	2.50	0.40	0.40	2.00	CPEI_GPS
244.695	32.419	37.20	-38.50	-7.20	0.40	0.40	1.40	CPIG_GPS
244.693	32.418	39.40	-38.80	-6.60	0.60	0.40	2.00	CPVO_GPS
244.727	32.588	12.20	-11.10	-0.10	0.40	0.40	1.40	FI18_GPS
244.524	32.633	15.20	-16.70	2.10	0.40	0.40	1.60	MEXI_GPS
243.831	32.467	-8.10	-2.40	-1.70	0.40	0.40	1.60	COND_GPS
244.613	31.772	-3.20	4.50	3.20	0.40	0.40	1.40	SALD_GPS
244.042	31.973	-5.60	-0.10	-1.60	0.40	0.40	1.60	RAYO_GPS
244.946	31.492	-1.70	3.60	2.00	0.40	0.40	1.60	ELCH_GPS
244.165	31.624	-1.20	0.30	-0.30	0.40	0.40	1.80	SM01_GPS
243.332	31.872	-1.70	-0.50	-0.20	0.40	0.40	1.40	RM01_GPS
243.332	31.872	-2.10	-0.90	0.10	0.40	0.40	1.40	RM02_GPS



Objective Function

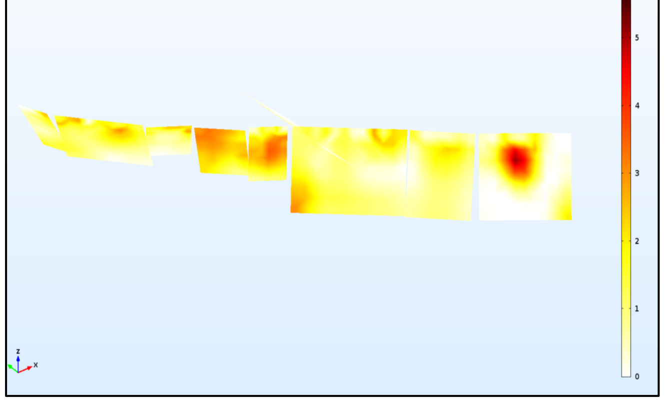
Minimize the sum of the cost functions

$$\left(\frac{Umod_i - Umeas\_i}{Umeas\_err\_i}\right)^2 + \left(\frac{Vmod_i - Vmeas\_i}{Vmeas\_err\_i}\right)^2 + \left(\frac{Wmod_i - Wmeas\_i}{Wmeas\_err\_i}\right)^2$$

i= index for the station

Optimization is performed with SNOPT algorithm (Gill et al.[2005]) using the adjoint method

Starting slip distribution



New slip=starting Slip*c

c=control variable

where c_0=1 and 0≤c≤2
(KKT conditions)

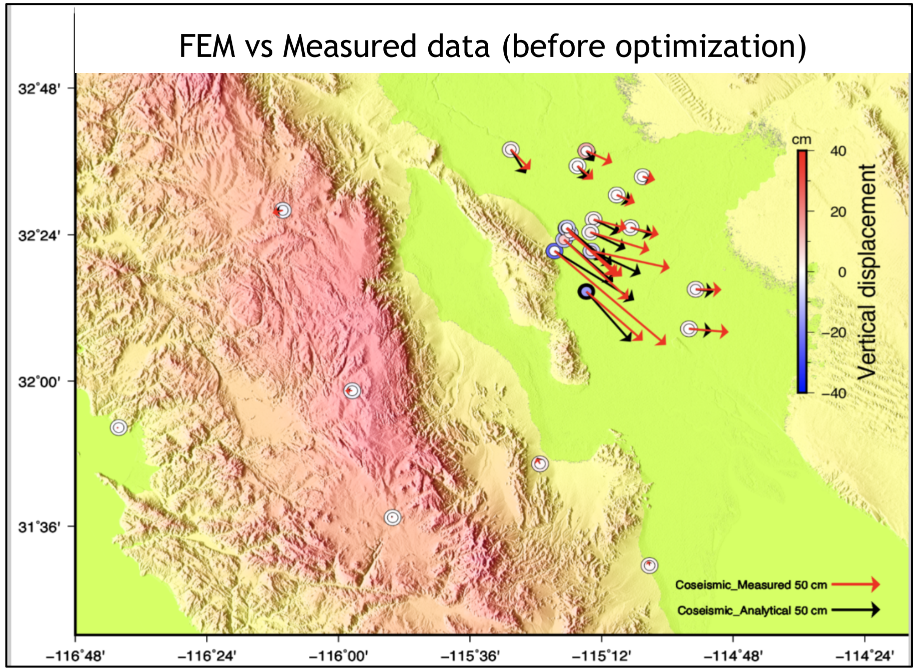
Smoothing

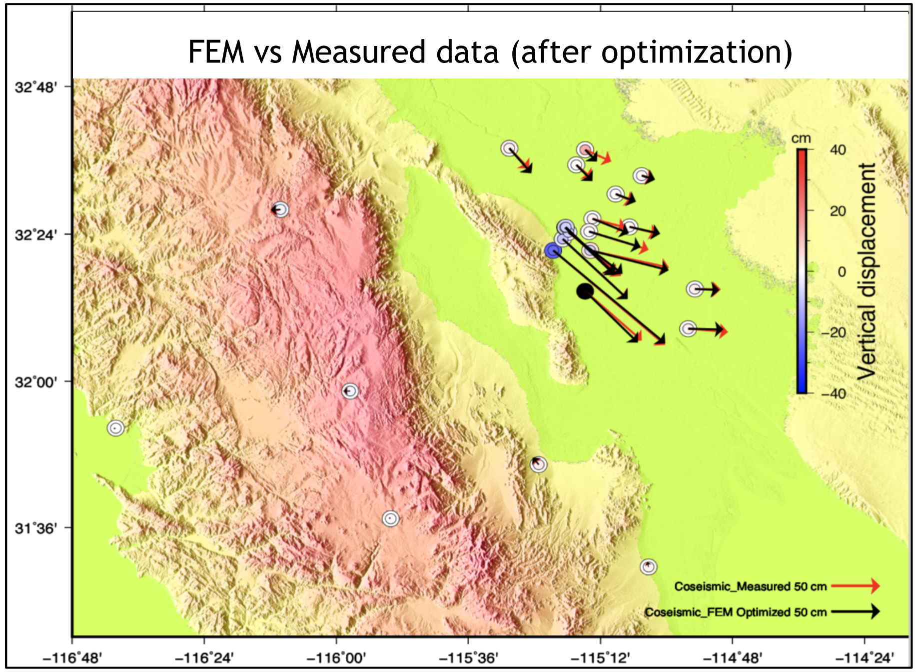
$$\boxed{-1e^{-3}} \le dtang(c,x) + dtang(c,y) \le \boxed{1e^{-3}}$$

Data Stand Dev

Model Variance

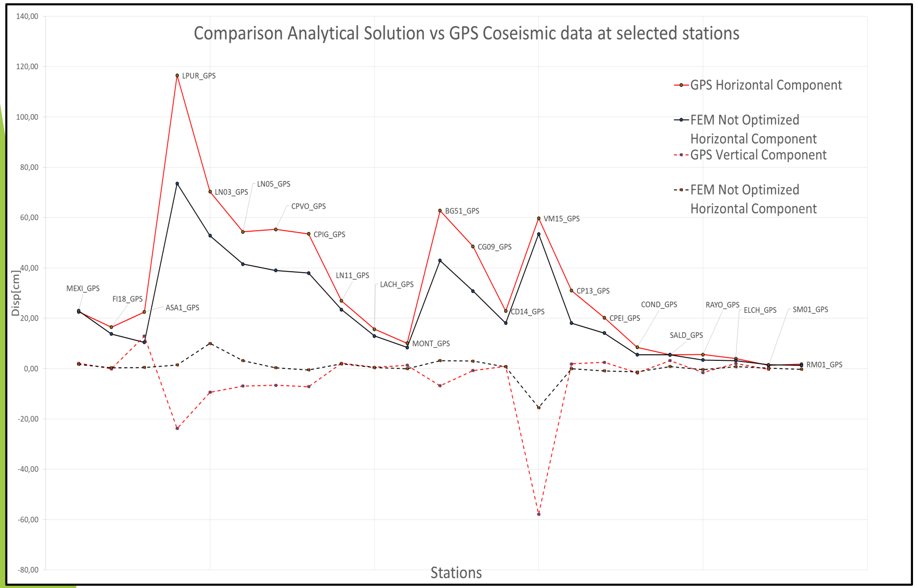
Inverse models: Solution at Mexican CICESE campaign GPS stations (near-field). Optimized in homog config.

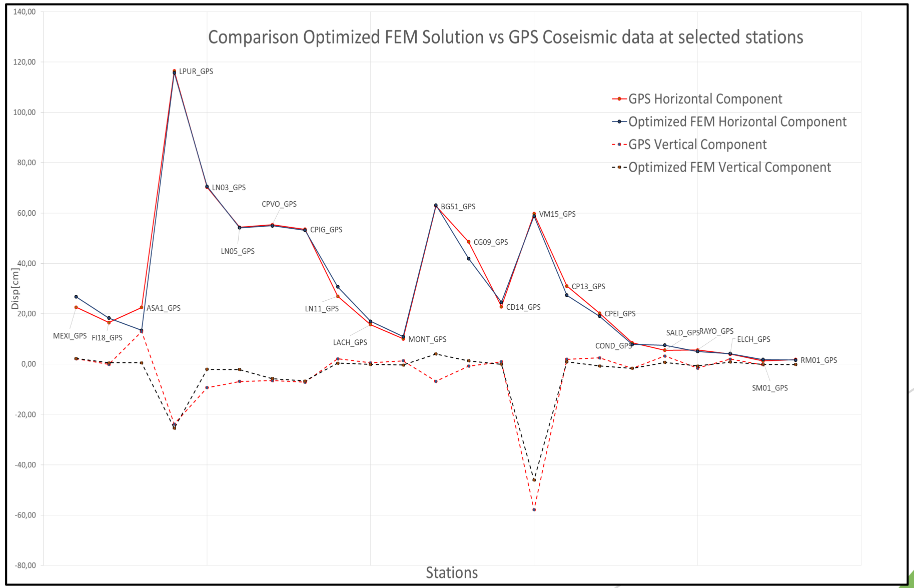


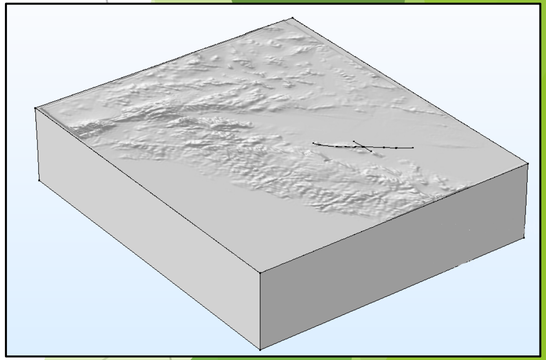


The vectors of the optimized solution well match with the ones from measured GPS data

Horizontal and vertical components are improved



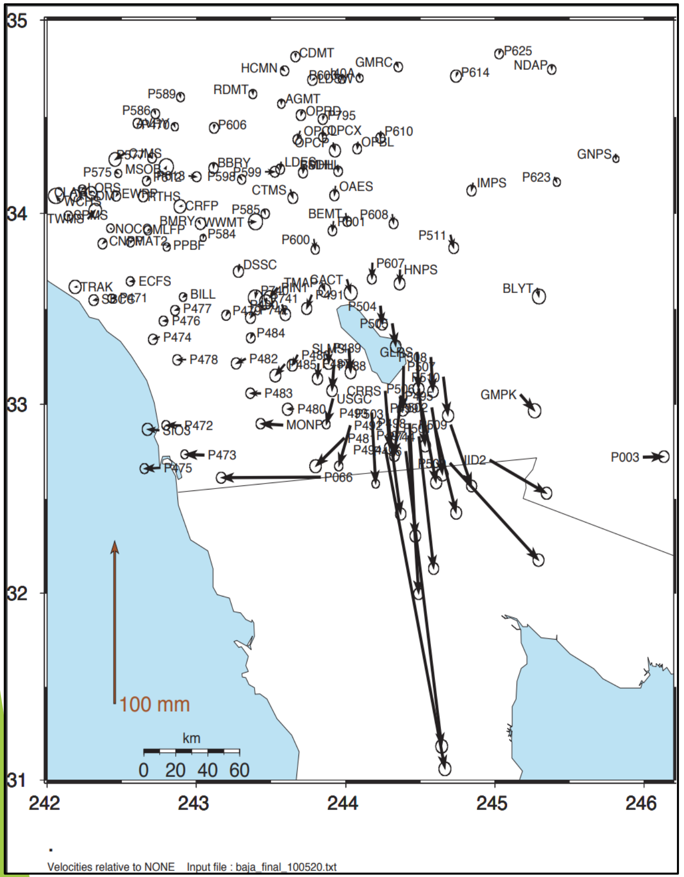




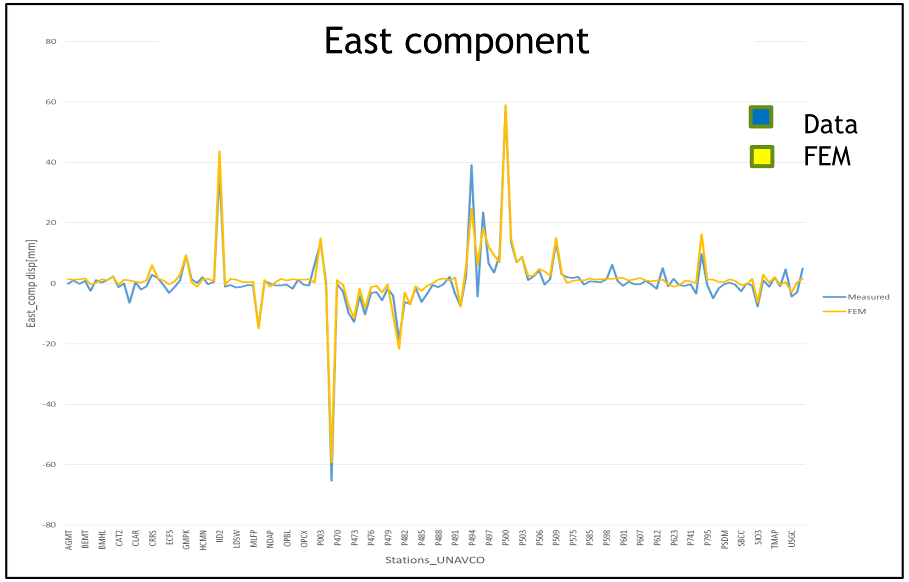
Solution changes is negligible when DEM is considered

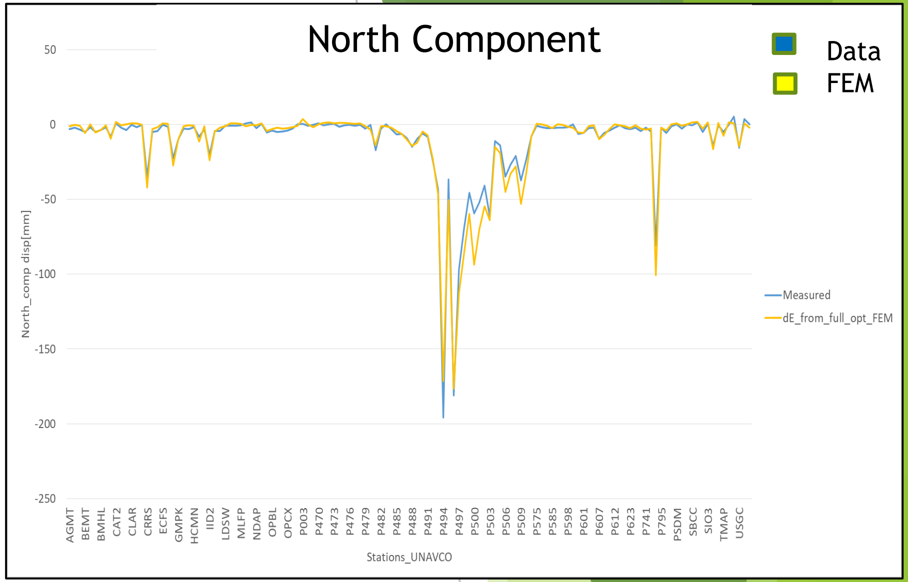
Do surface displacements from optimized near-field match at far-field stations?

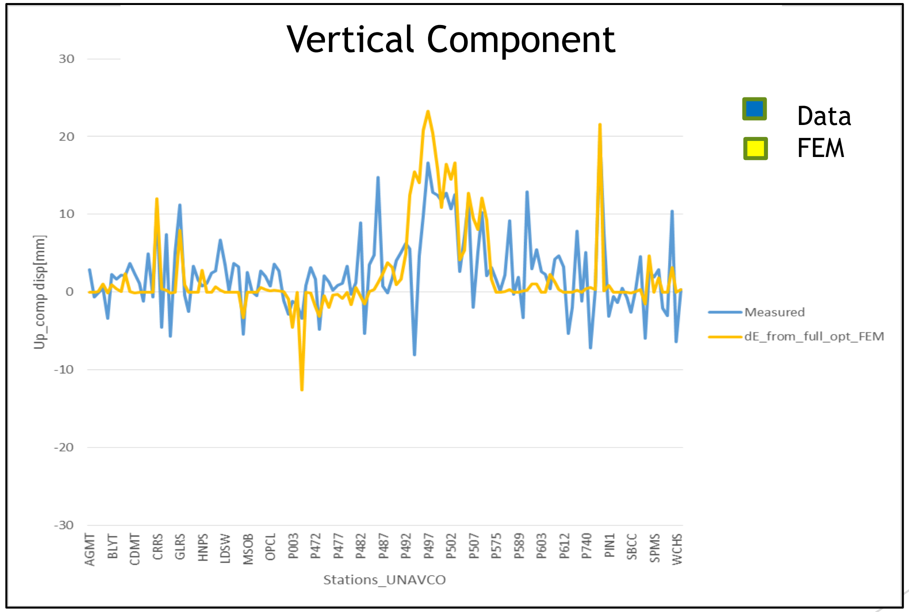
Used UNAVCO GPS stations



UNAVCO data from: ftp://data-out.unavco.org/pub/products/sinex/



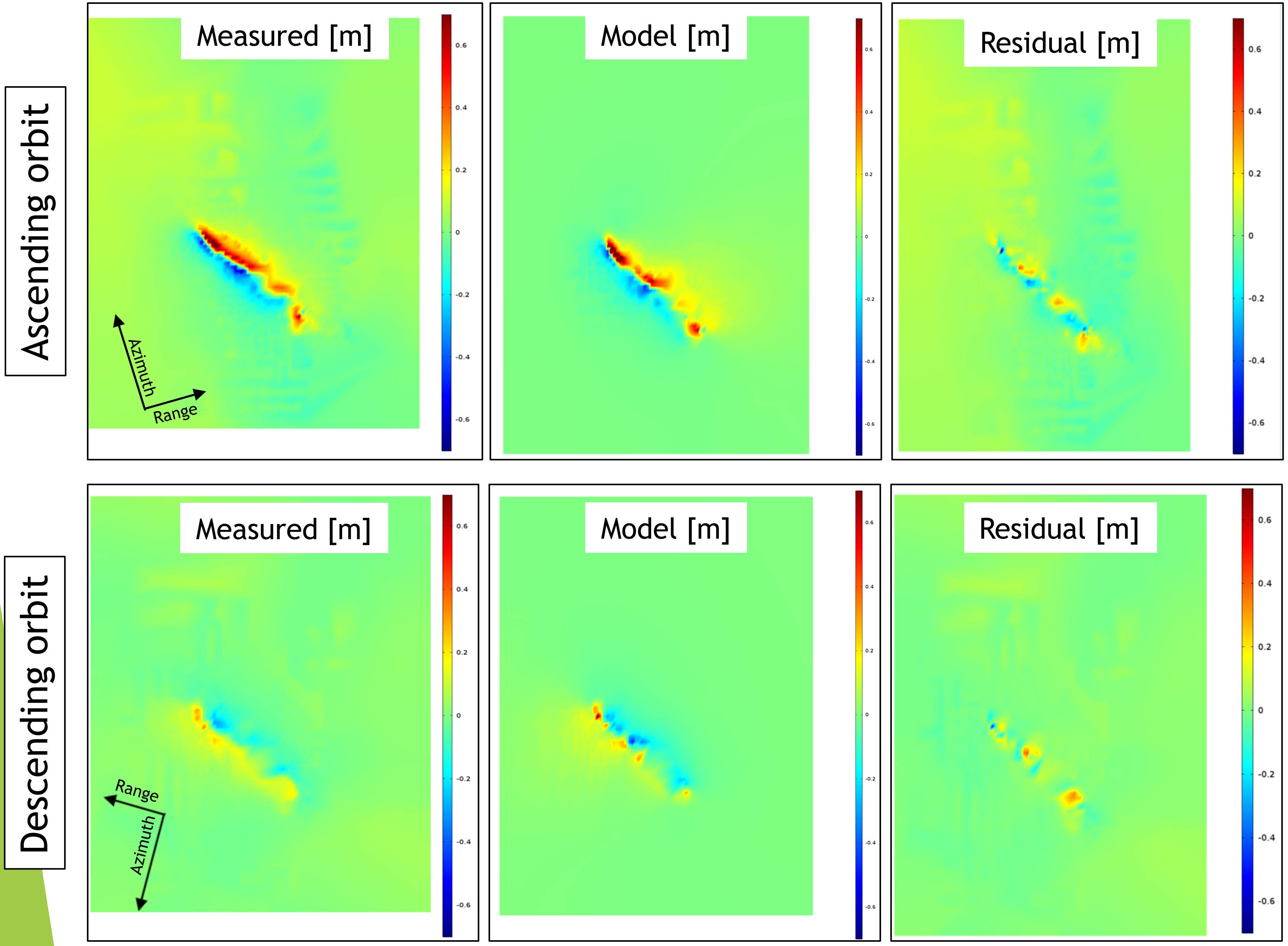




Horizontal components are well captured

FEM vertical comp. is smaller than the measured one

Do surface displacements from optimized near-field match InSAR data?

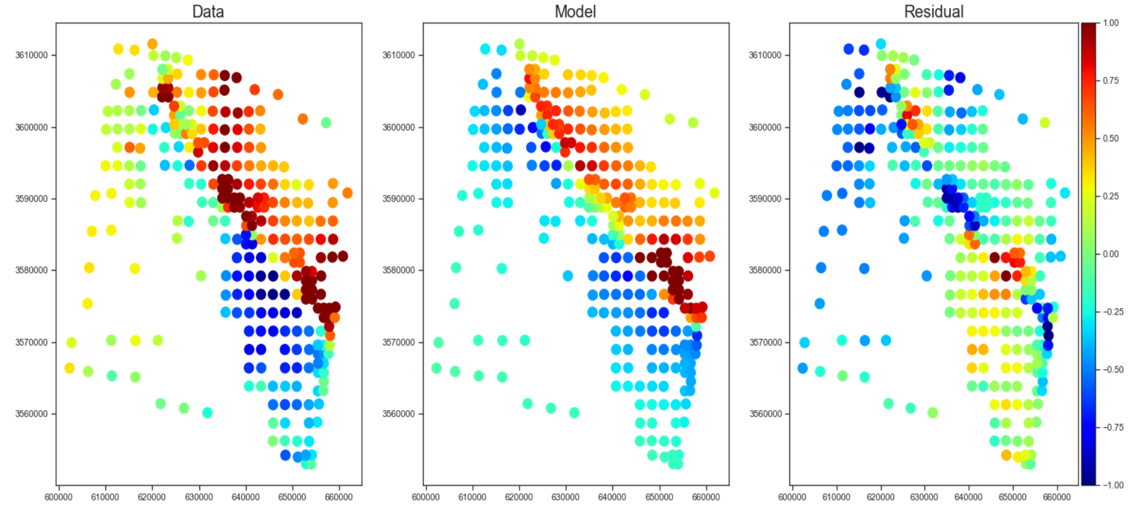


Track	Master (dd/mm/yyyy)	Slave (dd/mm/yyyy)
ALOS PALSAR		
A210	31/03/2010	16/05/2010
A211	15/01/2010	17/04/2010
A212	17/12/2009	04/05/2010
D533	30/11/2009	17/04/2010
Envisat ASAR		
A077	28/03/2010	02/05/2010
A306	09/03/2010	13/04/2010
D084	12/03/2010	16/04/2010
D313	28/03/2010	02/05/2010
D356	09/03/2010	13/04/2010

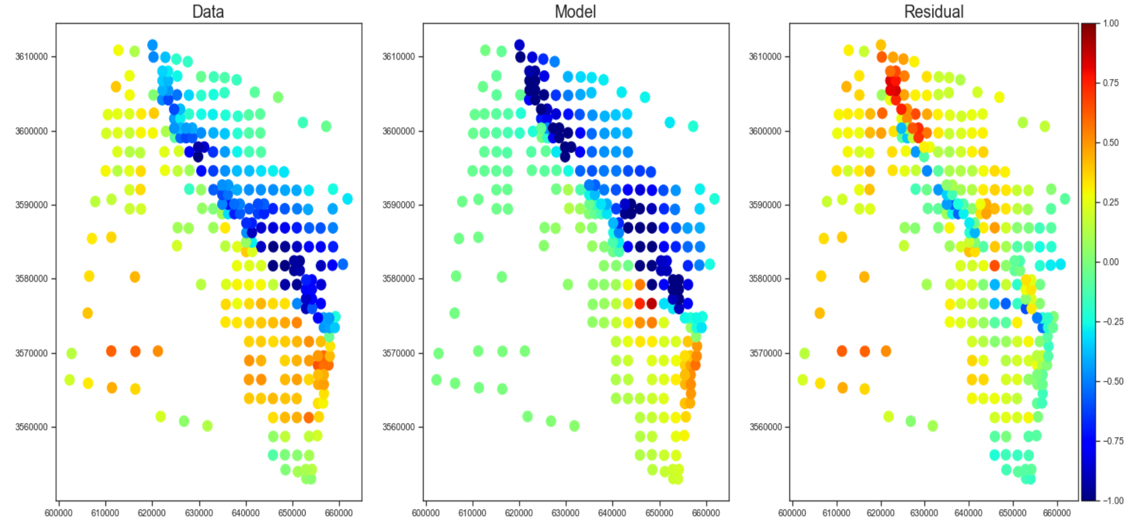
Residuals	Standard Deviation
SAR_minus_FEM_ascending_homog	0,109
SAR_minus_FEM_ascending_layered	0,110
SAR_minus_FEM_ascending_heterog	0,107
SAR_minus_FEM_descending_homog	0,075
SAR_minus_FEM_descending_layered	0,084
SAR_minus_FEM_descending_heterog	0,081

Do surface displacements from optimized near-field match subpixel offset data?

Subpixel offset data comparison: E-W component



Subpixel offset data comparison: N-S component

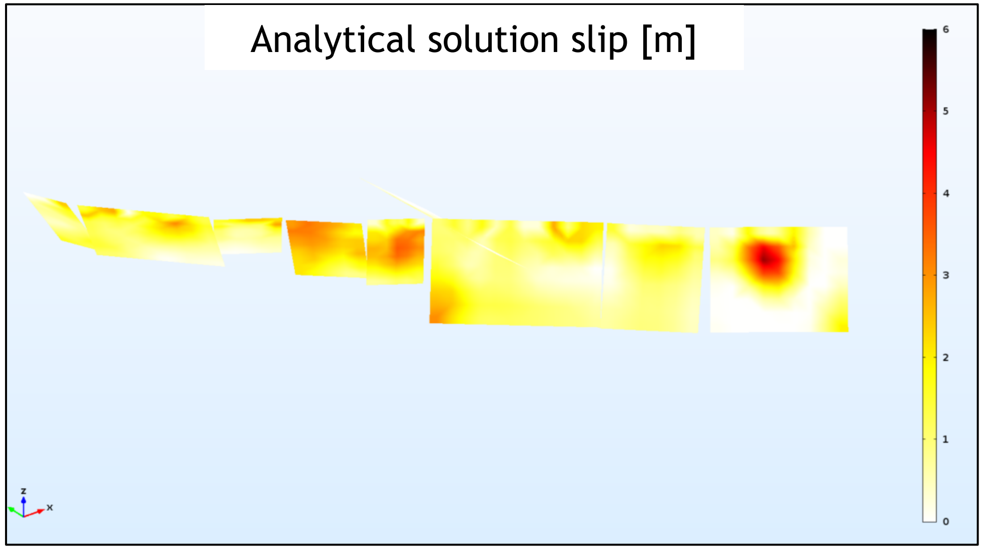


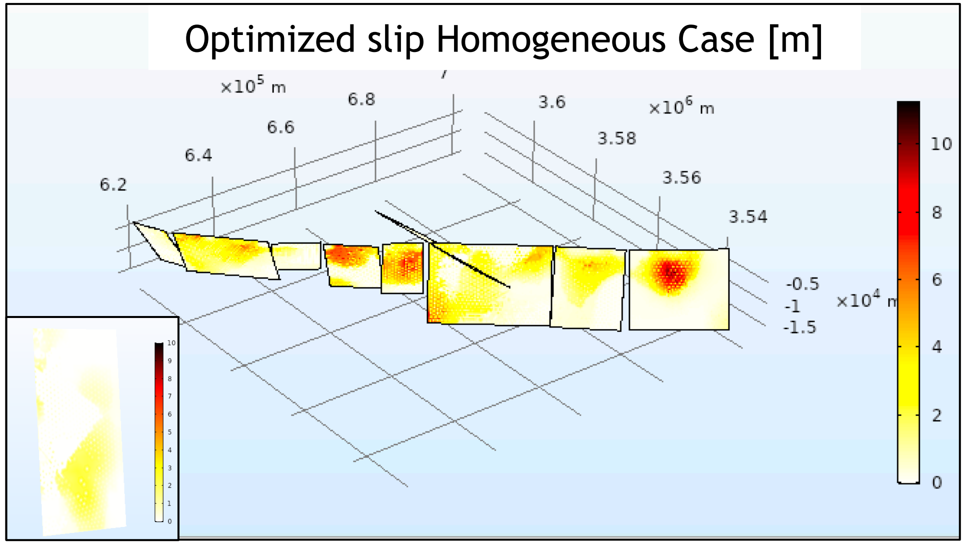
Model Config	Stand Deviation
Residual_E-W_subpixoff_homog	0,422
Residual_E-W_subpixoff_layered	0,403
Residual_E-W_subpixoff_heterog	0,400

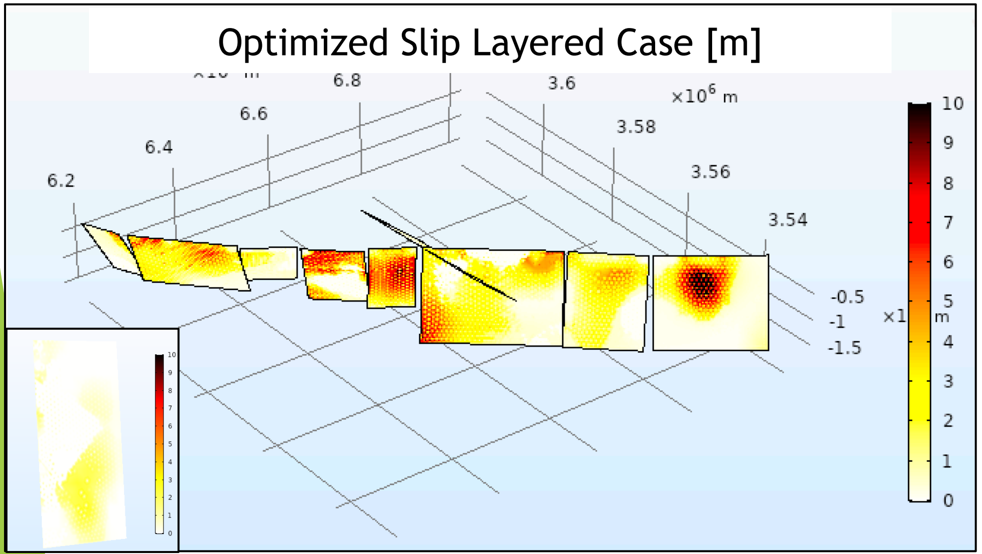
SPOT5 (Range and Azimuth)			
Master (dd/mm/yyyy)	Slave (dd/mm/yyyy)		Geometry Inversion
26/05/2009	08/04/2010		X
SAR			
Track	Master (dd/mm/yyyy)	Slave (dd/mm/yyyy)	Satellite
A306 (range and azimuth)	09/03/2010	13/04/2010	Envisat
A211 (azimuth)	15/01/2010	17/04/2010	ALOS
A212 (azimuth)	17/12/2009	04/05/2010	ALOS
D313 (range and azimuth)	28/03/2010	02/05/2010	Envisat

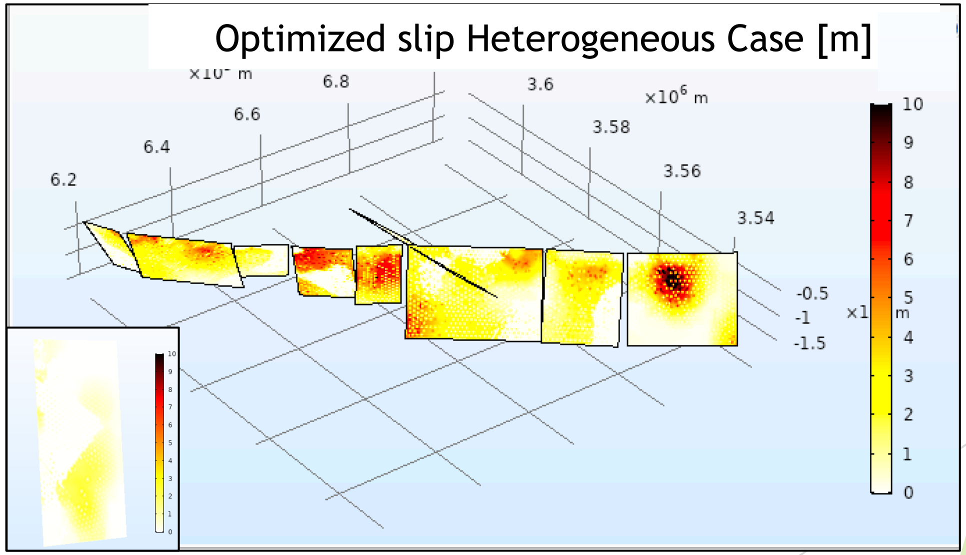
Model Config	Stand Deviation
Residual_N-S_subpixoff_homog	0,311
Residual_N-S_subpixoff_layered	0,339
Residual_N-S_subpixoff_heterog	0,333

Inverse models: How does the optimized solution modify the slip?









Main findings

Slip is enhanced in the optimized solution (peak up 10m)

Slip increase at depth for layered and heterogeneous cases

In all optimized solutions the slip on planes 1 and 3 is strongly reduced

Plane 2, 6, 7 and 9 slip distrib. is similar to the starting solution but 1m bigger in layered and heterogeneous cases

Slip on plane 4 is mostly above 8km depth

Slip on plane 5 is about 1 m bigger in homogeneous case and 2 m bigger in layered and heterogeneous cases

Slip on plane 8 is about 2 m bigger in the homogeneous case and about 3 m bigger in the layered and heterogeneous cases.

New slip distribution and calculus of seismic moment

Seismic Moment $M_0 = \mu * D * A$ μ=shear modulus[N/m^2]; D=slip[m]; A=Fault plane area [m^2]

Moment Magnitude $M_w = 2/3 * \text{Log}10(M_0) - 6.04$

Model configuration	M_w_Analytic_GPS Huang et al[2017]	M_w_FEM (optimized)	GMT value
Homogeneous	7.26	7.24	7.2
Layered	7.32	7.33	
Heterogeneous	N/A	7.36	

Moment magnitude from optimized FEM solution is consistent with analytical values

Results

- FEM model highlights the need to optimize the initial solution;
- Optimized FEM solution fits well near-field GPS stations and horizontal components of far-field GPS stations;
- Optimized FEM solution has minimal residuals when compared to InSAR and subpixel offset data.
- Topography contribution is negligible while heterogeneities increase the slip at depth;
- Slip distribution is strongly reduced on planes 1 and 3 and shallower on plane 4 (up to 8km depth)
- Slip values increase to give a proper fit the observation with the heterogeneous case somehow in between the homogeneous (smallest) and layered (strongest) slips;
- Seismic moment calculated from the new slip is consistent with the values calculated analytically and similar to the recorded value (GMT solution).

Conclusion: Our finite element provides a new slip distribution whose outputs are in agreement with different datasets. Provided solution is promising and can give new hints to better understand the dynamics of a complex event like El Mayor Cucapah.

Next steps

- Perform joint inversion of the different datasets
- Perform checkerboard tests to evaluate the robustness of our optimization
- Include material non-linearities and investigate viscoelastic postseismic relaxation

Thank you